Example of Data Telemetry for Biomedical Applications: an In Vivo Experiment

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***Abstract*—This letter describes a data telemetry biomedical experiment. An implant, consisting of a biometric data sensor, electronics, an antenna and a biocompatible capsule is described. All the elements were co-designed, in order to maximize the transmission distance. The device was implanted in a pig for an in vivo experiment of temperature monitoring.**

***Index Terms*—Implantable Antennas, Biomedical Telemetry.**

I. Introduction

The introduction of pacemakers in the early 1960s and the first swallowable pills with sensing capabilities have shown the importance of implantable devices, enabling the monitoring and the treatment within the human body. Today, Radio-Frequency (RF) applications contribute to disease prevention, diagnosis and therapy [1]. Glucose monitoring, insulin pumps, deep brain stimulation and wireless endoscopy are a few examples of medical applications that could take advantage of remote monitoring and control to improve the patient's comfort and care [2].

Generally speaking, implantable communications in a range of few meters call for the design of both small and efficient antennas which makes their design very challenging.

The first use of radiators inside a living body dates back as far as five decades [3] and many antenna designs have been proposed since then (recent examples are [4]–[6] while a review can be found in [7].

Although previous designs mainly target the Industrial, Scientific and Medical (ISM) 2.45 GHz frequency range, the Medical Device Radiocommunication Service band (MedRadio, 401-406 MHz) has been recently allocated for implant communication [8]. Therefore, this work mainly focuses on the latter frequency range.

Implants should minimize their volume in order to facilitate the surgical procedure. This implies that implantable antennas must be heavily miniaturized, leading to the design of Electrically Small Antennas (ESA) with dimensions much smaller than the free space wavelength (typically $\lambda_0/30$ in the MedRadio). On top of the antenna design, it is mandatory to adhere to a global system point of view and to follow a multidisciplinary approach, in order to efficiently transmit information outside the lossy human body. Let us refer to Fig. 1 which describes a telemedicine application for indoor use. From left to right, it is clear that the Base Station (antennas, electronics), the channel propagation, the human body and the implanted device (materials, antennas, packaging, electronics, power supply, sensor) are all aspects that must be considered to accomplish a successful communication.

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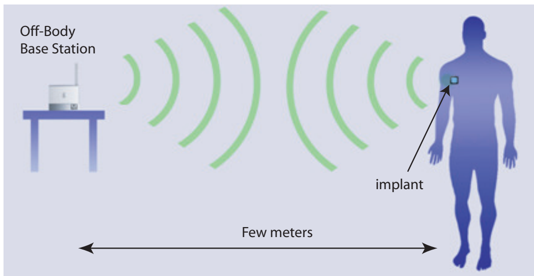


Fig. 1. Sketch of a bi-directional home health-care system with a wireless implantable device in a Wireless Body Area Network with a range of few meters (2-5 m).

In this letter, we present an example of data telemetry in an in vivo experiment. The experiment consists in monitoring the local temperature of a pig after a skin graft using autologous stem cells. A temperature sensor is mounted in a implantable module to be placed both under the pig skin and in depth (30 mm in the muscle). The module is composed of off-the-shelf communication electronics, a custom made antenna and batteries. The antenna and the bio-compatible packaging were co-designed in order to optimize the power transmission out of the host body. The base station consists of readily available communication electronics, two antennas and a control unit. The aim of the experiment was to allow data telemetry transmission without disturbing the ongoing medical experiment. A wireless reading distance out of the host body (a living pig) of more than 10 meters was thus required.

This letter is organized as follows. In Section II, the implantable module is described, while Section III is dedicated to the base station. The data transmission experiment and its results are discussed in Section IV. Conclusions are drawn in Section V.

II. Description of the Implantable Module

The proposed module (known also as Body Sensor Node, BSN) reaches a high system integration of all its components, namely: the Multilayered Spiral Antenna (MSA), the electronics (the RF transceiver and the Digital Signal Processor), the batteries and the bio-sensor. Figure 2 depicts the complete packaging of the device. All the elements fit in a biocompatible cylindrical housing which measures 10 x 32 [mm]. The MSA

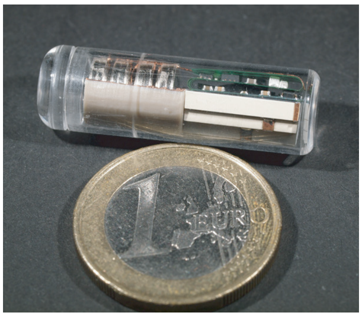


Fig. 2. Multilayered Spiral Antenna integrated in a complete Body Sensor Node [9], [10]. For a better visualization, PEEK insulation is substituted by Polymethyl methacrylate (PMMA).

consists of a conformal radiator, whose main resonating is developed on a *pyramidal* assembly and around the power supplies as described in [9]. Polyetherketone (PEEK) was chosen for the biocompatible housing and its thickness (0.8 mm) was selected to improve the electromagnetic radiation of the implanted radiator in agreement with the results reported in [11]. The MSA has dual band capabilities (MedRadio and ISM bands). Its radiation performances, predicted maximum gain equal to -29.4 and -17.7 dBi in the lower and higher frequency ranges respectively, ensure a robust communication link for applications targeting a minimum working range of 2 m.

The electronics components were assembled on a flexible printed circuit board [12]. The RF communication is provided by the Zarlink ZL70101 Integrated Circuit [13] operating in both the MedRadio and ISM bands. The BSN operations are executed by an ultra-low power digital signal processor: the Ezairo 5900 manufactured by ON Semiconductor. Four coin type 377 batteries (1.5 V/ 27 mAh), manufactured by Energizer, were selected to provide the required power supply: a pack comprising 2 batteries are connected in series to give the 3.1 V and two packs are connected in parallel. The total energy for 1 measurement with RF transmission is 6.85 mJ lasting for 532.4 ms, whereas the total energy during the sleep state is 0.55 mJ. If each measurement occurs every 300 s (see Section IV), the mean power consumption is (6.85+0.55)/300 = 24.7 uW. That corresponds to a life time of 273 days with our 4 coins batteries.

Table I summarizes the power parameters measured during the in-vitro measurement campaign described in [10]. The in-vivo experiment considered the same setup exception made for the different BSN antenna gain when implanted into the pig, and the BS arrangement and antennas described in the following Section.

The conception of the proposed BSN gives a broad freedom regarding the monitoring device or bio-actuator to be included.

TABLE I
Power Link Budgets - In Vitro Characterization [10].

Parameter	**MedRadio**		**ISM**
	BSN to BS	BS to BSN	BS to BSN
Frequency	401 MHz		2.45 GHz
Tx power [dBm]	-3.0	-11.0	20
Tx antenna gain [dBi]	-30.5	-5	0
EIRP [dBm]	-33.5	-16.0	20.0
Free space path loss (2.5 m) [dB]	32.5		48.2
Fade Margin [dB]	5.0		2.5
Rx antenna gain [dBi]	-5.0	-29.4	-18.6
Rx power [dBm]	-76.0	-82.9	-49.3
Rx sensitivity [dBm]	-95.0	-99.0	-53.0

The temperature sensor used in this experiment, the front-end electronics to drive the glucose microviscometer presented in [14] and the potentionstat described in [15] illustrate the versatility of the realized BSN.

III. Description of the Base Station Module

In order to realize a telemedicine system with remote monitoring capabilities, the Base Station comprises:

- a Zarlink receiver module;
- an antenna for each working band;
- an image acquisition system;
- a 3G USB modem;
- a laptop to drive the entire system and to store the measurements;

as illustrated in Fig. 3.

(a) (b)

Fig. 3. Base Station components: (a) a wireless camera placed in front of the animal cage (b) a laptop, the Zarlink external module and antennas all enclosed in plastic boxes.

Given the fixed orientation between the base station and the cage of the animal (see Section IV), a cavity-backed double patch radiator [16] and a helix were used in the MedRadio and ISM bands, respectively. These radiators, having a maximum gain of 7-8 dBi, substituted the omnidirectional antennas of the Zarlink receiver module (used in Table I). As the animal is free to move within the cage, which modifies the relative orientation between the MSA and the base station antennas, the radiators have circular polarization in order to avoid fading.

In order to monitor the pig position, we implemented an image acquisition system triggered at each data communication. The uCam module from 4D Systems, depicted in Fig. 3-(a), was connected to the laptop via Bluetooth.

The laptop was connected to a 3G USB modem to enable a remote desktop connection. Figure 4 shows the graphical user interface when remotely accessing the laptop. Finally, to protect it from dust and other environment hazards, the entire Base Station was enclosed in plastic boxes as depicted in Fig. 3-(b).

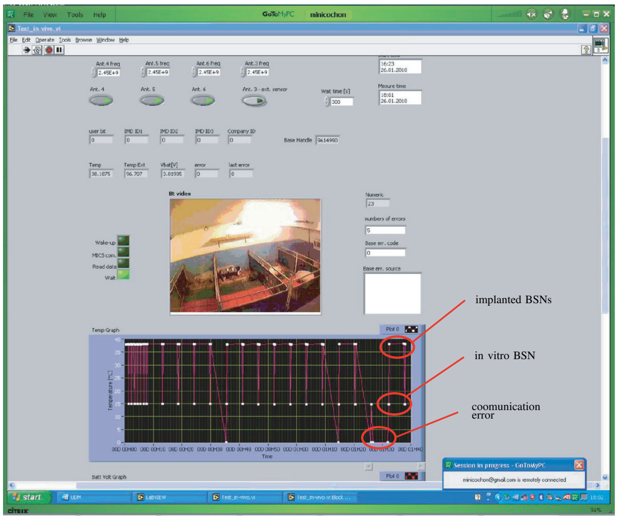
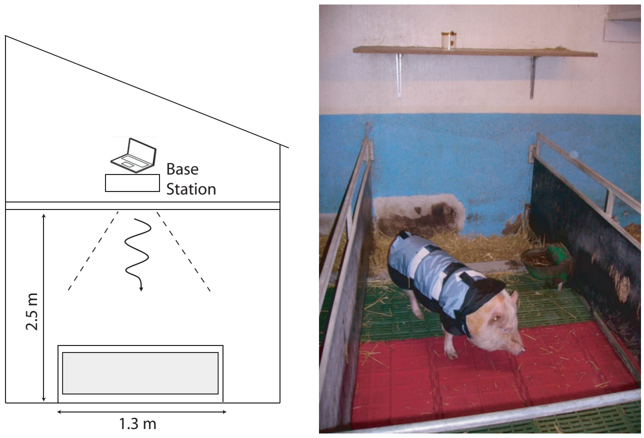


Fig. 4. LabView graphical user interface when remotely connected. Temperature values of the three BSNs (two implanted, one in vitro) are recorded and displayed. The picture at the center shows the pig position.



(a) (b)

Fig. 5. System Set-up at the farm: (a) cutting view (b) and pig in the cage which measures 1.3 x 2.7 [m].

IV. In Vivo Experiment

The data telemetry experiment was associated to a skin graft using stem cells carried out on a Göttingen minipig. Our interest focused on the impact that local temperature may have on the fate choice made by transplanted stem cells. Indeed, the temperature value gives a potentially important information on the local microenvironment to which stem cells have to adapt.

For this purpose, two implantable modules as described in Section II were implanted in the back of the pig, in accordance to ethical considerations and the regulatory issues related to animal experiments (experimentation demand no 1751-2 & 1751-3, Canton de Vaud, CH). The subcutaneous and intra-muscular depths of the implant were around 5 mm and 28 mm, respectively.

A. System Set-up

The off-body Base Station was placed in the attic above the cage room as illustrated in Fig. 5. This choice protected the external receiver from the cage cleaning, movement of animals and/or people and from any risky actions that may occur in the cage room.

B. Data Telemetry

Local temperature values were measured every five minutes by both implanted BSNs for a consecutive period of fifteen days. The time lag between each temperature was set following medical requirements. The results are reported in Fig. 6. At first sight, one can appreciate that the intra-muscular implant recorded always a higher temperature (+0.2° C) than the subcutaneous one. The circadian rhythm of the pig is also observable: the lowest temperature occurred around 5-6 h as the pig was sleeping, and the highest around 18-19 h. Finally, a rise of the skin temperature was observed during the day 8, most likely due to a local inflammation due to suboptimal wound healing and pathogen invasion.

C. Wireless Communication Reliability

During the whole experiment, we performed 2696 data acquisitions per BSN. Each measurement includes the complete wireless communication cycle: wake-up of the implant with a 2.45 GHz signal, bi-directional data transmission in the MedRadio band and return of the BSN to its sleeping state.

Several parameters were identified as sources of error for the RF communication, namely:

- relative position of the animal with respect to the base station;
- selection of the channel in both MedRadio and ISM bands;
- distribution of the EM field in the cage room (standing waves);
- physiological recovery of the animal tissues.

Figure 7 reports the number of relative errors per day during the experiment period. The RF issues have been classified according to the working frequency, whereas malfunctioning of the driving software are named as “firmware”. Our in-vivo campaign showed that:

- the subcutaneous BSN had a higher reliability (less errors) than the intra-muscular one. Indeed, its less deep implantation facilitated the RF transmission;

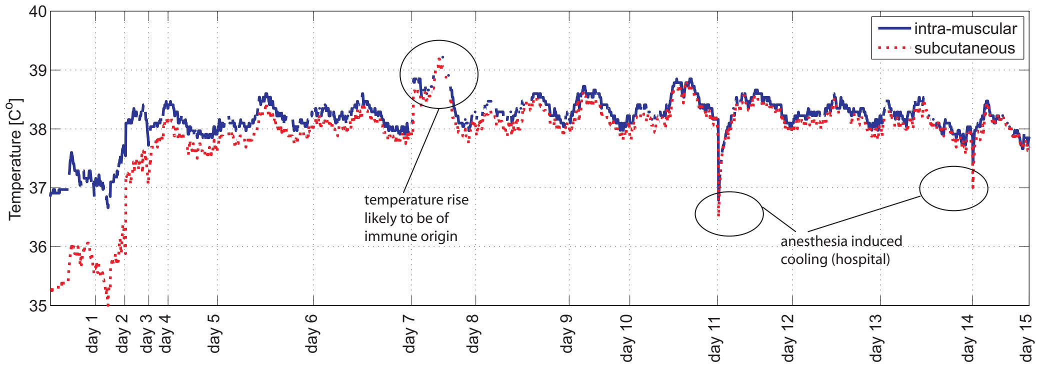


Fig. 6. Measured temperature over fifteen days by the implanted BSNs. Temperature minima are related to wound cleaning and treatment at the hospital. Time-line is not constant as different number of measurements were taken during each day. Pig central normal temperature = 38.3°- 39.0° C.

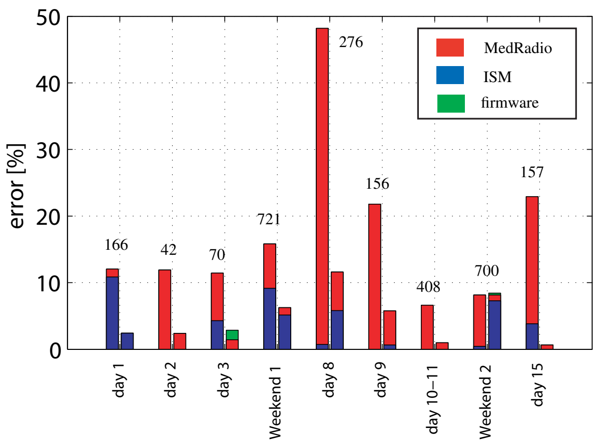


Fig. 7. Relative communication errors of the wireless communication over the fifteen days implantation: first column always identifies the intra-muscular BSN, while the second column relates to the subcutaneous one. Relative values are always calculated with respect to the number of measurements reported above each set of columns.

- the animal does sleep on the side the surgery took place. This position completely prevents the communication;
- the ISM wake-up was the principal problem observed during the first day. Modifications of the BS position and of the channel for the 2.45 GHz signal had a positive effect on the experiment;
- the MedRadio errors became predominant starting from day 2. The worst performances, reaching almost 50% of failure for the intra-muscular BSN, were recorded during the day 8. Experimental evidence suggested that the local inflammation -evident in the corresponding temperature increase in Fig. 6- implied a variation of the dielectric characteristics of the tissues, thus a shift of the MSA MedRadio resonance;
- the modification of the MedRadio channel and treatment of the infection improved the performances for the subsequent days. Nonetheless, MedRadio errors increased again at the end of the second week (> 20% again for the intra-muscular BSN) possibly because of the non optimal suturing.

In conclusion, the performances are satisfying despite the presence of a high number of errors during some days: the relative errors over all the measurements, $\mathrm{err}_{\mathrm{tot}}$, are below 20% and 10% for the intra-muscular and subcutaneous BSNs, respectively, as reported in Table II.

TABLE II
COMMUNICATION ERRORS DURING THE 15-DAYS IN-VIVO EXPERIMENT.

BSN	**Meas.**	$\mathrm{err}_{\mathrm{Med}}$ [%]	$\mathrm{err}_{\mathrm{firm}}$ [%]	$\mathrm{err}_{\mathrm{ISM}}$ [%]	$\mathrm{err}_{\mathrm{tot}}$ [%]
intra-muscular	2696	12.46	0.00	3.63	16.09
subcutaneous	2696	1.67	0.11	4.04	5.82

V. CONCLUSION

An in vivo experiment of data telemetry for a biomedical application has been presented demonstrating the viability and usefulness of such systems. The goal was to monitor the skin temperature of a pig after cultured epidermal autograft transplantation. The implanted device, composed of an antenna, the electronics, the battery, the bio-sensor and the bio-compatible packaging has been described. All these components have been jointly designed to both achieve a high system integration and optimize the power transmission out of the host body. The base station required to realize a telemedicine system with remote monitoring capabilities has also been presented. Finally, the in vivo experiment has been detailed and the data transmission results have been discussed in order to better identify the challenges of real life applications. For instance, on the one hand it is worth suggesting to consider the bandage over the pig skin wound during the antenna design (as pointed out in [11]); indeed the bandage may still interact with the antenna near field and thus contribute to the overall radiator's efficiency. On the other hand, the use of a cold blade to create the pig skin wound will certainly avoid any healing problem or local skin infection.

REFERENCES

[1] A. Rosen, M. A. Stuchly, and A. Vander Vorst, "The role of engineering principles in the medical utilization of electromagnetic energies from kHz to visible light - examples," *International Journal of Infrared and Millimeter waves*, vol. 30, no. 12, pp. 1374–1386, Dec. 2009.

[2] R. Bashirullah, "Wireless implants," *IEEE Microwave*, vol. 11, no. 7, 2010.

[3] R. S. Mackay, "Radio telemetering from within the body: inside information is revealed by tiny transmitters that can be swallowed or implanted in man or animal," *Science*, vol. 134, no. 3486, pp. 1196–1202, Oct. 1961.

[4] T. Karacolak, R. Cooper, J. Butler, S. Fisher, and E. Topsakal, "In vivo verification of implantable antennas using rats as model animals," *IEEE Antennas Wireless Propagat. Lett.*, vol. 9, pp. 334–337, 2010.

[5] M. L. Scarpello, D. Kurup, H. Rogier, D. Vande Ginste, F. Axisa, J. Vanfleteren, W. Joseph, L. Martens, and G. Vermeeren, "Design of an implantable slot dipole conformal flexible antenna for biomedical applications," *IEEE Trans. Antennas Propagat.*, vol. 59, no. 10, pp. 3556–3564, 2011.

[6] O. H. Murphy, C. N. McLeod, M. Navaratnarajah, M. Yacoub, and C. Toumazou, "A pseudo-normal-mode helical antenna for use with deeply implanted wireless sensors," *IEEE Trans. Antennas Propagat.*, vol. 60, no. 2, pp. 1135–1139, Feb. 2012.

[7] A. Kiourti and K. Nikita, "A review of implantable patch antennas for biomedical telemetry: Challenges and solutions [wireless corner]," *Antennas and Propagation Magazine, IEEE*, vol. 54, no. 3, pp. 210 –228, June 2012.

[8] *Medical Device Radiocommunications Service (MedRadio),*, Federal Communication Commission (FCC) Std. CFR, Part 95, formerly Medical Implanted Communication System (MICS).

[9] F. Merli, L. Bolomey, J. Zurcher, G. Corradini, E. Meurville, and A. K. Skrivervik, "Design, realization and measurements of a miniature antenna for implantable wireless communication systems," *IEEE Trans. Antennas Propagat.*, vol. 59, no. 10, pp. 3544–3555, 2011.

[10] F. Merli, L. Bolomey, F. Gorostidi, Y. Barrandon, E. Meurville, and A. K. Skrivervik, "In vitro and in vivo operation of a wireless body sensor node," in *Proc. of the 2^{nd}International ICST Conference on Wireless Mobile Communication and Healthcare*, 5-7 Oct. 2011.

[11] F. Merli, B. Fuchs, J. R. Mosig, and A. K. Skrivervik, "The effect of insulating layers on the performance of implanted antennas," *IEEE Trans. Antennas Propagat.*, vol. 59, no. 1, pp. 21 –31, Jan. 2011.

[12] L. Bolomey, E. Meurville, and P. Ryser, "Implantable ultra-low power DSP-based system for a miniature chemico-rheological biosensor," in *Proceedings of the Eurosensors XXIII conf.*, no. 1, 2009, pp. 1235 – 1238.

[13] P. D. Bradley, "An ultra low power, high performance medical implant communication system (MICS) transceiver for implantable devices," in *Proc. IEEE Biomedical Circuits and Systems Conference BioCAS 2006*, Nov. 2006, pp. 158–161.

[14] S. Kuenzi, E. Meurville, and P. Ryser, "Automated characterization of dextran/concanavalin a mixtures–a study of sensitivity and temperature dependence at low viscosity as basis for an implantable glucose sensor," *Sensors and Actuators B: Chemical*, vol. 146, no. 1, pp. 1 – 7, 2010.

[15] G. De Micheli, S. Ghoreishizadeh, C. Boero, F. Valgimigli, and S. Carrara, "An integrated platform for advanced diagnostics," in *Proc. Design, Automation and Test in Europe (DATE 2011)*, 2011, pp. 2995–2999.

[16] S. Lopez-Peña, J.-F. Zürcher, R. Torres, A. G. Polimeridis, and J. R. Mosig, "Modeling and manufacturing of a series of identical antennas for a P-band ice sounder," in *Proc. Fourth European Conf. Antennas and Propagation (EuCAP)*, 2010, pp. 1–5.